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Report

Color Constancy for an Unseen Surface

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Summary

The illumination of a scene strongly affects our perception of objects in that scene, e.g., the pages of a book illuminated by candlelight will appear quite yellow relative to other types of artificial illuminants. Yet at the same time, the reader still judges the pages as white, their surface color unaffected by the interplay of paper and illuminant. It has been shown empirically [1] that we can indeed report two quite different interpretations of "color": one is dependent on the constant surface spectral reflectance of an object (surface color) and the other on the power of light of different wavelengths reflected from that object (reflected color). How then are these two representations related? The common view, dating from Aristotle, is that our experience of surface color is derived from reflected color or, in more familiar terms, that color perception follows from color sensation [2–4]. By definition, color constancy requires that vision "discounts the illuminant"; thus, it seems reasonable that vision begins with the color of objects as they naively appear and that we infer from their appearances their surface color. Here, we question this classic view. We use metacontrast-masked priming and, by presenting the unseen prime and the visible mask under different illuminants, dissociate two ways in which the prime matched the mask: in surface color or in reflected color. We find that priming of the mask occurs when it matches the prime in surface color, not reflected color. It follows that color perception can arise without prior color sensation.

Results

Experiment 1

The aim of this experiment was to determine whether the color of an unseen object is represented in terms of its reflected color or its surface color. That is, can color constancy be computed for an object that elicits no experience? Metacontrast masking [5], which extinguishes the experience of a briefly presented stimulus through the use of a subsequent mask, was used to render a colored prime invisible. Success of this method depends upon the interstimulus delay, in addition to the spatial, temporal, and chromatic properties of the stimuli. The color of the prime speeds color recognition of the mask, but only when the prime and mask match in color. In this experiment, the prime and mask were presented under different illuminants, one resembling direct sunlight (Commission Internationale de l'Eclairage [CIE] D50), and the other resembling average daylight (CIE D65). Two mask colors were chosen so as to match either the prime's surface color (blue mask) or the prime's reflected color (green mask). See Figure 1, Table S1 available online, and Supplemental Experimental Procedures for information on chromaticities. Figure S1 illustrates the spectral properties of the two illuminants. All experiments were covered by approval from the Durham University Psychology Department Ethics Committee.

The experiment consisted of two separate phases. In the first phase, the priming phase, participants completed three sessions in which they identified the color of the mask as quickly as possible. The prime was presented 50 ms before the onset of the mask for durations of either 12.5 ms or 37.5 ms. The prime was absent in half of the trials, and we refer to these trials as having a 0 ms prime presentation time. See Figure 2 for an illustration of the sequence of events in a single trial (see Figure 2 legend and Supplemental Experimental Procedures for details on how the illuminant was changed). We quantified a single measure of the prime's effect by taking the difference between its effect on response times (RTs) for masks matched in reflected color (measured relative to when the prime is absent) and the same measure for masks matched in surface color. The resultant measure was the surface priming advantage (SPA), which, when positive, implies that the color of the prime was congruent in terms of surface color and, when negative, implies that it was congruent in reflected color. The SPA was significantly above zero at both prime duration levels (mean SPA = 25.8 ms for short prime duration, and mean SPA = 31.4 ms for long prime duration; $t_{(9)} = 4.801$, $p = 0.001$ and $t_{(9)} = 5.120$, $p = 0.001$, respectively). All results are shown in Figure 3.

In the second phase of the experiment, the detection phase, participants completed three sessions in which they judged whether the prime was present or not on a confidence scale of 1 to 8 (the nature of the prime was demonstrated to them in a much slower presentation of stimuli prior to beginning this phase). The discriminability index (d_a) was calculated using the software RScorePlus [6] to fit a Gaussian unequal-variance signal detection model to these data. Overall, d_a did not differ significantly from zero for either level of prime duration (mean $d_a = -0.006$ for short prime duration, and mean $d_a = 0.186$ for long prime duration; $t_{(9)} = 0.162$, $p = 0.875$ and $t_{(9)} = 1.823$, $p = 0.102$, respectively), which indicates very strongly that participants had no experience of the prime. The individual signal detection results indicate that just two participants could detect the presence of the long duration primes. No participants were able to detect the short duration primes.

Experiment 2

This experiment tested whether the results can be explained by participants learning to anticipate how surfaces under D50 would appear under D65, given that observers attended to a location that invariably underwent this illuminant change on each trial. Such a strategy would be consistent with some inferential theories of color constancy (see discussion in [7]).

Here, we eliminated the predictability of the illuminant change; we randomly interwove trials with an illuminant change with those in which the illuminant did not change. Nevertheless, the SPA for illuminant-change trials remained significantly above zero (mean SPA = 69.5 ms for short prime duration, and mean SPA = 43.6 ms for long prime duration; $t_{(9)} = 3.359$, $p = 0.008$ and $t_{(9)} = 2.685$, $p = 0.025$, respectively),

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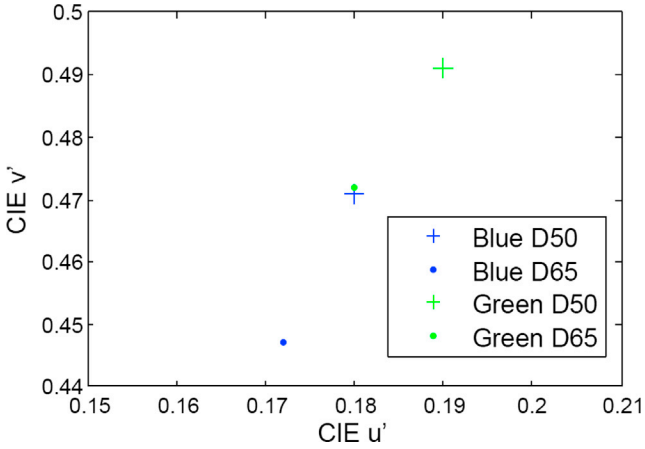

Figure 1. Chromaticities for the Blue and Green Surfaces

Chromaticities for the blue and green surfaces when illuminated by D50 or D65, specified in CIE u′ v′ space. The blue and green filled dots in the plot represent the chromaticities of the blue and green masks, respectively, seen under D65. The crosses represent the same surfaces seen under D50. The prime display is illuminated by D50, and the prime is identical in chromaticity to that of the blue mask under the prime's illuminant (surface-color match) but is nonetheless physically identical to the green mask in terms of reflected color (reflected-color match). See Figures S1 and S3 for further details and for modeling of the effects of adaptation to the stimuli.

and participants' d_a did not differ significantly from zero (mean d_a = 0.000 for short prime duration, and mean d_a = 0.159 for long prime duration; $t_{(9)}$ = 0.007, p = 0.994 and $t_{(9)}$ = 1.479, p = 0.173, respectively; two participants could detect the presence of the prime at the long duration). The priming effects are unlikely to have arisen as a result of implicit learning.

Experiment 3

Here, we sought to eliminate the possibility that the priming effect was due to constancy of color contrast. The ratios of cone excitations in response to light reflected from adjacent surfaces remain approximately constant across an illuminant change [8]. In this study, the prime and mask appeared over the intersection of four background squares, so there was no single contrast to prime, lessening the probability that contrast constancy explains color priming. However, to eliminate this possibility, we added a dark chromatic annulus to both the outer and inner edges of the mask in experiment 3, thereby removing the common set of local contrasts shared between prime and mask. The SPA was again significantly above zero (mean SPA = 14.2 ms for short prime duration, and mean SPA = 28.9 ms for long prime duration; $t_{(9)}$ = 2.467, p = 0.036 and $t_{(9)}$ = 5.186, p = 0.001, respectively), and participants' d_a did not differ significantly from zero (mean d_a = −0.057 for short prime duration, and mean d_a = 0.038 for long prime duration; $t_{(9)}$ = 1.193, p = 0.263 and $t_{(9)}$ = 0.737, p = 0.480, respectively). Thus, the priming effect was not dependent on equivalence in local contrast between the prime and mask.

Experiment 4

We have discussed the surface priming advantages observed in experiments 1–3 in terms of constancy for surface color. Constancy can, however, also affect judgments made about reflected color [1, 9]. Adaptation in the retina that scales neural responses in proportion to the prevailing strength of signals from each cone class (von Kries adaptation) can affect all cortically mediated responses to color. Can our results be explained in terms of such low-level mechanisms? In Arend and Reeves's [1] original experiments, participants adjusted the color of one patch under one illuminant to match that of another patch under a different illuminant in accordance with the following instructions: (1) "make the samples look as if cut from the same paper," or (2) "make the samples match in hue and saturation." The first yields a large degree of constancy, and we believe this instruction taps our ability to represent surface color, whereas the second yields a very small, but nonetheless present, degree of constancy, which we believe taps representations of reflected color. If low-level mechanisms of constancy produced the priming effects in this study, then they would lead to a degree of constancy in representations of the prime's reflected color.

In experiment 4, we measured separate indices of constancy for surface color and reflected color between the prime and target by using unmasked primes (made visible by extending their presentation duration) to show that only the surface-color constancy can explain the priming effect. On a scale where 0.00 represents perfect inconstancy and 1.00 represents perfect constancy, the average degree of reflected-color constancy did not differ significantly from zero (0.00; $t_{(9)}$ = 0.034, p = 0.973), whereas that of surface-color constancy did (0.65; $t_{(9)}$ = 7.355, p < 0.001). This value of surface-color constancy is consistent with that found in other experiments (normal average of 0.66 [9]), but it is unusual to find a complete absence of reflected-color constancy (normal average 0.23). A control condition showed that this anomaly is the result of presenting the prime and mask sequentially in the same spatial location. When the prime and mask were presented simultaneously but were spatially separated under different illuminants, the degree of reflected-color constancy was 0.29 ($t_{(9)}$ = 5.499, p < 0.001). Together, these measurements provide strong evidence that the unseen prime was represented in terms of its surface color and that the results of experiments 1–3 could not be explained in terms of retinal adaptation.

Retinal adaptation nevertheless often does affect constancy for reflected-color judgments. Why does it not do so in our experiments? Effects on reflected-color judgments are typically found in experiments in which there is a wholesale change of illumination across the visual scene. In our experiments, we shift the boundary between two areas of illumination a small distance and therefore have much weaker changes in the overall color of stimuli. We modeled how von Kries adaptation would affect the signals elicited by the stimuli in our experiments. These models suggested that retinal adaptation cannot account for the findings of experiments 1–3 (the modeling is described in the Supplemental Experimental Procedures; Figure S3 and Table S2 illustrate the modeling results). The similarity of color signals between the prime and mask should determine priming. Even after adaptation, the modeled signals from reflected-color masks are still more similar to primes than those from surface-color masks.

Discussion

These experiments used a metacontrast-masked priming task in which the prime and mask were presented under different illuminants; we showed that an unseen prime speeds the color recognition of the mask if they share surface color, not reflected color. The priming effect did not result from implicit learning across trials, i.e., from the acquired ability to

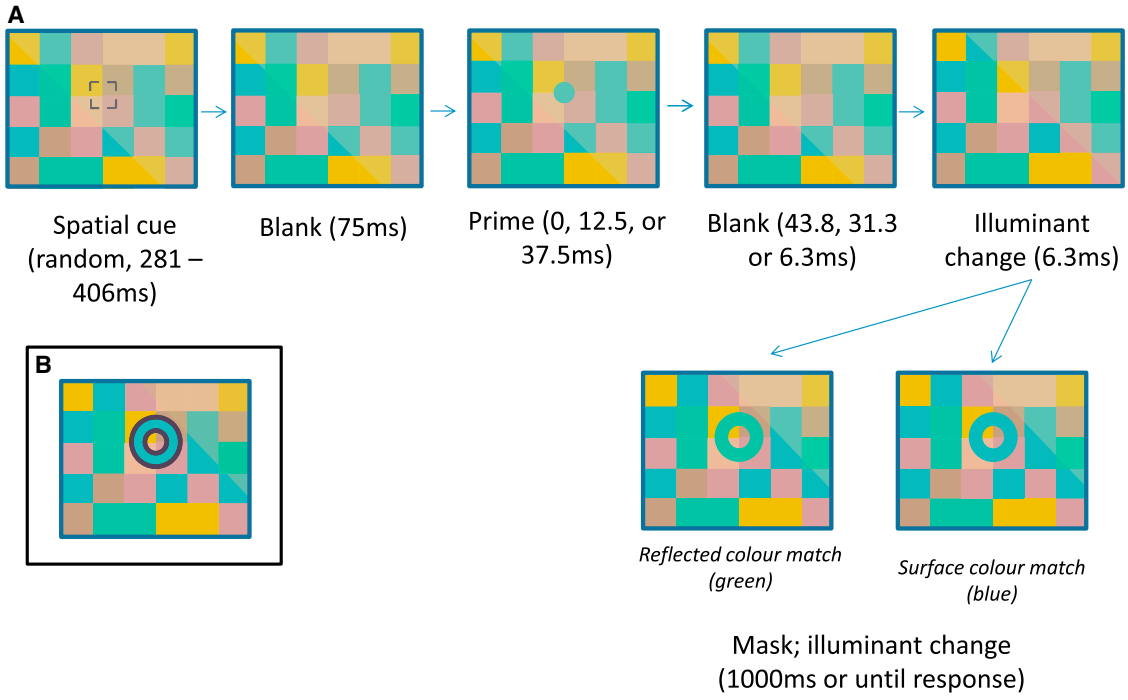

Figure 2. Stimuli Presented in an Experimental Trial

(A) Experiment sequence. The sequence of an individual trial is shown, from left to right. An initial cue indicates the location of the prime and mask. After a delay, the prime is then presented for a variable duration, either 0 ms (prime absent), 12.5 ms, or 37.5 ms, and the duration of the following "Blank" display is dependent on the duration of the prime in order for the prime mask stimulus onset asynchrony and the overall display duration to be kept constant across conditions. During the presentation of the prime, the scene is illuminated in one half by D50 and in the other half by D65, with the illuminant boundary bisecting the scene at an angle of 45°. The prime always appears in the D50 half. After the offset of the prime and before the onset of the mask, the illuminant boundary moves such that the target will appear under the D65 illuminant. The mask is shown in its two potential colors: the green is congruent with the prime in reflected color, but the blue is congruent in surface color. Note that the figure is only an illustration of the stimuli—color and scale of stimuli are not accurate.

(B) Mask with inner and outer border annuli. The dark chromatic annuli around the inner and outer regions of the mask annulus ensured that the mask and prime colors did not share a common chromatic contrast with the background in experiment 3.

anticipate the effects of the illuminant change on the mask's appearance (experiment 2). Also, the priming effect was not explained by the constant chromatic contrasts of the prime and mask with their checkerboard backgrounds (experiment 3).

Previous studies have provided good evidence that at least some aspect of color constancy is automatic and possibly nonconscious. Barbur and Spang [10] showed that when we have no conscious access to an illuminant change, color constancy is not diminished, and Foster et al. [11] have demonstrated that we detect violations in color constancy without attentional scrutiny. The present study provides the first strong evidence that the perception of surface color can occur in the absence of prior color sensations, at least insofar as we understand "color sensations" as the conscious experience of (something akin to) reflected color.

This finding may appear to be at odds with a previous study [12], which found that although a white prime was more easily confused with a blue mask than a green mask, it acted as a congruent prime for the green mask on the basis that it was more similar in terms of the luminances of the RGB guns of the monitor. Unlike in the present study, however, the prime was not matched with the masks in either surface or reflected color, so the priming effect might be driven by some other stimulus attribute, such as color contrast (whose impact is minimized in our experiments). To our knowledge, the present study is the first to use a change in illuminant conditions in order to dissociate surface and reflected color.

This study sheds light on the stage of processing in which surface color is estimated. The anatomy of color vision shows a clear progression from midget ganglion cells in the retina, where neural responses are determined primarily by the wavelength composition of light, to striate cortex, where cells responding to wavelength [13] and wavelength contrast [14] are found, and extrastriate areas that appear to compute color constancy [15, 16]. One potential constancy mechanism relies exclusively on rapid adaptation of photoreceptors in the retina [17]. As indicated by the complete absence of constancy in participants' perception of reflected color under conditions of the priming task (experiment 4), however, such adaptation can be ruled out as an explanation of our results because any mechanism operating prior to signals entering striate cortex is certain to modulate our experience of reflected color (or hue, saturation, and brightness).

Another mechanism, not based on local adaptation processes and relying on spatial interactions, is extremely rapid and likely to have a cortical basis [18]. This is likely to be associated with color contrast cells in striate cortex [14, 19], which could signal the stable property of relative surface color under a changing illuminant given that cone excitation ratios between adjacent surfaces are invariant under such a change. It is important to note, however, that the priming effect we

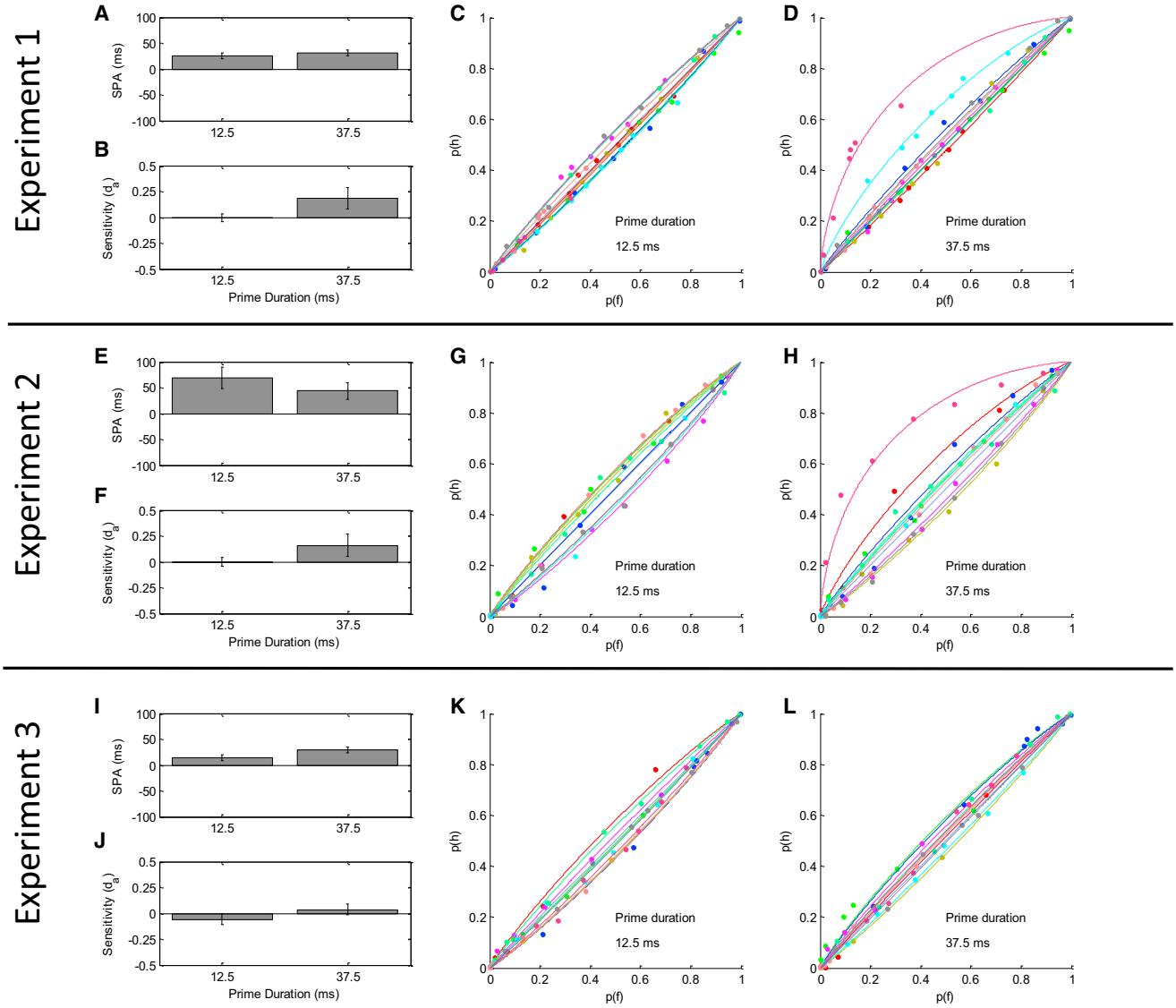

Figure 3. Results

The left panel shows the mean surface priming advantage (SPA; upper panel) and sensitivity calculations for detecting primes at short and long durations. The SPA is positive in all cases, indicating that the priming effect was driven by matches in surface color and not reflected color. In comparison, the sensitivity indices (d_a) do not differ significantly from zero, indicating very strongly that participants had no experience of the prime. Error bars show ±1 SEM. The middle and right panels show receiver operating characteristic (ROC) curves for each participant for detecting the prime at the short and long onset durations, respectively. ROC curves plot hit rate against false alarm rate across an individual's criteria range. The ROC curves showing sensitivity at the long onset durations (right panel) indicate that just two participants could detect the primes in experiments 1 and 2. In contrast, no participants could detect the primes at the short onset duration in any experiment or at either duration in experiment 3. See also Figure S2 for separate RTs to blue and green masks as a function of prime duration.

(A–D) Experiment 1 results.

(E–H) Experiment 2 results.

(I–L) Experiment 3 results.

observed cannot simply be explained by priming at the level of color contrast and is instead likely to necessitate a representation of surface color beyond that in striate cortex. Cells in monkey extrastriate area V4 modify their chromatic sensitivity in accordance with changes in background color [20], and areas in human cortex, including the fusiform gyrus, have been implicated in similar roles [10, 21]. It is entirely plausible that the unseen prime in the present task evoked such extrastriate processing, given that masked unseen primes are known to elicit activity in occipitotemporal areas [22]. Reduction in the visibility of masked color primes by a metacontrast mask probably occurs in early cortical areas V2 and V3 [23], but, presumably, the initial signal elicited by the primes can progress beyond these areas.

In neuropsychology, it is clear that the neural bases of color constancy and color experience are difficult to distinguish [13]; in cases of cerebral achromatopsia [24, 25], wherein color experience is lost, there is also no measurable implicit perception of surface color [26] and therefore no color constancy. Indeed, in Zeki's model of color perception, it is V4

that is the site of both constancy and experience [16, 27], but the two are nonetheless functionally separate, at least to the extent in which experience remains intact while constancy is impaired [16, 28]. The results from the present study suggest that the reverse dissociation can hold: color constancy can occur in the absence of color experience. One candidate area for the neural correlate of color experience [29] lies anterior to the constancy areas implicated in these studies, and there is some controversy over whether any of the earlier stages give rise to color experience [30], so one might speculate that estimates of surface color might feed into color experience.

Supplemental Information

Supplemental Information includes Supplemental Experimental Procedures, three figures, and two tables and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2014.10.009.

Author Contributions

L.J.N., C.A.H., and R.W.K. designed the experiments. L.J.N. ran the experiments and analyzed the data. All authors contributed to writing the manuscript.

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